NSWCCD-50-TR-2000/028 Stern Wave Topography and Longitudinal Wave Cuts Obtained on Model 5415, With and Without Propulsion

David Taylor Model Basin
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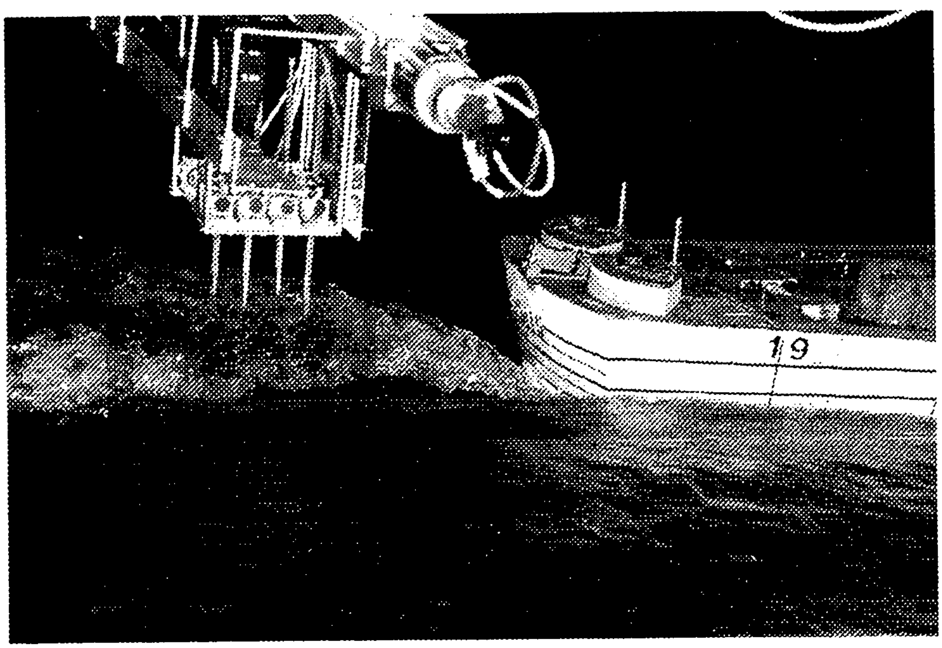
RESISTANCE AND POWERING DEPARTMENT REPORT

Stern Wave Topography and Longitudinal Wave Cuts Obtained on Model 5415, With and Without Propulsion

By
Toby J. Ratcliffe
Ian Mutnick
James Rice



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Experimental measurements of the Kelvin wake and the near and far field wave field, both with and without the model propeller operating, were obtained from a surface ship model representing the preliminary design of the DDG-51 hull form, represented by DTMB Model 5415. Wave height measurements were performed in the Carriage II basin at DTMB (David Taylor Model Basin) using two different techniques. The first technique uses capacitance probes attached to the side of the model basin to obtain longitudinal wave cuts. The second technique uses mechanical probes attached to a traversing system at the stern of the model to measure the surface wave field behind the model. The data from the mechanical probes were used to generate a wave height topography map. The results from both measurement techniques are used as a basis for comparison with computational fluid dynamics (CFD) predictions..

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ABSTRACT

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ADMINISTRATIVE INFORMATION

The work described in this report was performed by the Resistance and Powering Department of the Hydromechanics Directorate, Carderock Division, Naval Surface Warfare Center. The work was sponsored by the Office of Naval Research, Mechanics and Energy Conversion S&T Division (Code 333) under the Hydrodynamics Task of FY99 Surface Ship Technology Program (PE0602121N). The work was performed under work unit 99-1-5200-053.

INTRODUCTION

An ONR Free Surface Flow Initiative for validating and transitioning Reynold's Averaged Navier Stokes computational codes was begun in 1995. Model 5415 was chosen as a representative naval combatant hull form on which a rigorous set of experimental data would be obtained. This report documents the free surface wave height data obtained on Model 5415, both with and without operating propellers.

MODEL DESCRIPTION

Model 5415 was built of wood in 1980 to a linear scale ratio of 24.824 and is representative of a modern naval combatant hull form. Electronic files representing the geometry of the hull form, both bare hull and with appendages can be downloaded from Reference 1. Figure 1 shows a photograph of the model fully outfitted for this experiment with removable appendages (shafts and struts). The model has twin rudders which are set at an angle of zero degrees relative to the model centerline. The model was not fitted with bilge keels. Turbulence stimulator studs 3.2 mm in diameter and 2.5 mm in height were fitted to the model in accordance with Hughes and Allen [2].

During the propelled experiments, the model was fitted with anodized aluminum design propellers designated as DTMB propellers 4876 and 4877. These represent 18-foot (5.49-meter) full-scale diameter propellers. A photograph of the propellers on the model is shown in Figure 2.

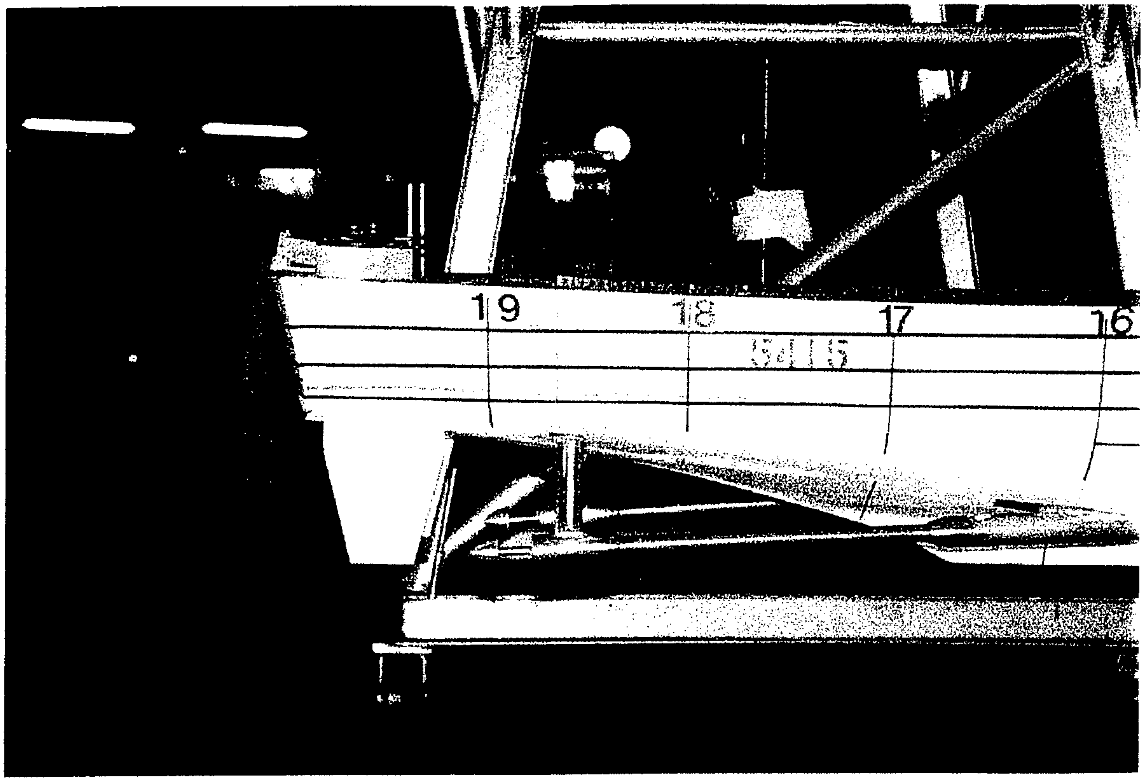

Figure 1 – Model 5415 with Removable Appendages (shafts and struts)

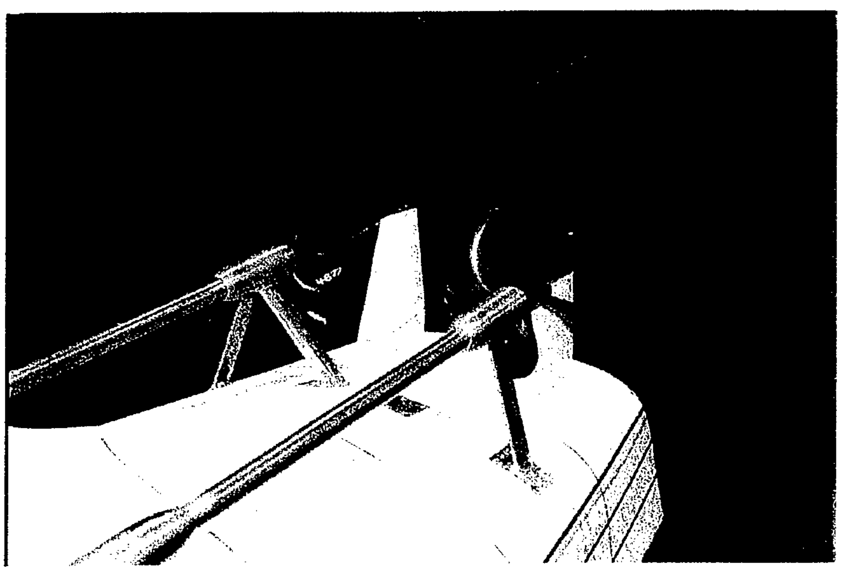

Figure 2 – DTMB Propellers 4876 and 4877 on Model 5415

Figure 3 shows an isometric view of the appended model. Table 1 documents model dimensions and other particulars.

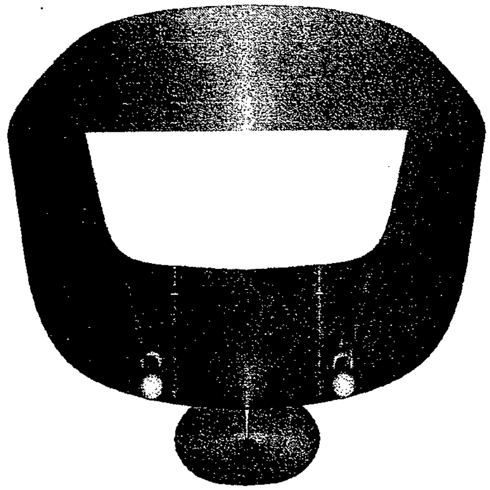

Figure 3 – Isometric View of Model 5415

	MODEL
Lambda	**24.824**
LBP , LWL	**18.768 ft (5.72 m)**
Displacement	**1210 lbs (548.8 kg)**
Appended Wetted Surface	**52.863 ft^2 (4.92 m^2)**
Sinkage at FP (Fn=0.28)	**-.0027L**
Sinkage at AP (Fn=0.28)	**-.00086L**
Sinkage at FP (Fn=0.41)	**-.00054L**
Sinkage at AP (Fn=0.41)	**-.0083L**
Propellers	**Port 4877 Starboard 4876**
Propeller Diameter	**8.7 inches (22.10 cm)**

Table 1 – Model 5415 Dimensions and Particulars

EXPERIMENTAL PROCEDURES

The experiments described herein were obtained both with and without the model propellers operating. In order to obtain the most accurate free surface measurements, in these experiments the model was mounted in a fixed trim condition corresponding to the running trim of the model at either a Froude number of 0.28 (6.77 ft/sec)(2.06 m/sec) or 0.41 (10.16 ft/sec) (3.10 m/sec). When the measurements were obtained with the propellers operating, the propeller RPM was set at the ship self-propulsion point. A table of operating conditions of the propellers during the propelled experiments is presented in Table 2.

Speed	K_T $K_T = T/(\rho D^4 n^2)$	K_Q $K_Q = Q/(\rho D^5 n^2)$	rpm	J V/nD
6.77 ft/sec (2.06 m/sec)	.178	.0461	436	1.28
10.16 ft/sec (3.10 m/sec)	.232	.0562	722	1.175

Table 2 – Propeller Operating Conditions
(K_T and K_Q determined from open water tests)

During these experiments, two techniques were used to measure wave heights generated by the model. The first technique measures longitudinal wave cuts using stationary capacitance probes. The second technique measures wave heights in a rectangular area using whisker probes. The following discussion of experimental procedures is divided by technique used, and then further divided into four sections; theory of operation, experimental setup, calibration, and operating procedures.

LONGITUDINAL WAVE CUT MEASUREMENTS

Theory of Operation

The sensing element of the capacitance probe is a 30 gauge (AWG) solid silver-plate copper wire with 0.045in. (.11mm) kynar insulation, approximately 15 inches (38.1 cm) in length. Attached to the sensing element is a weighted 4 ft. (1.21m) length of mylar fishing line, used to provide probe stability in waves. The sensing element is suspended with half its length submerged in the basin water. The basin water provides the ground reference for the sensing elements on the circuit card. With the copper wire completely insulated from the water, the sensing element behaves as a capacitor with one plate being the copper wire, the second plate the water, and the wire insulation acting as the dielectric. As waves in the basin change the submerged height of the sensing element, they change the effective capacitor plate size, which results in a change in capacitance. The change in capacitance is what allows the measurement of the wave height. By attaching the sensing element, a varying capacitor, to a timing circuit, a d.c. voltage is generated that is directly proportional to the capacitance of the probe and therefore the wave height being measured.

Experimental Setup

A truss section (wave boom), cantilevered from the basin wall over the water, provides a structure from which instrumentation is mounted. The wave boom extends 22.417 feet (6.83m) from the basin wall, which is approximately 3 feet (0.91m) short of the basin centerline. Mounted vertically on the wave boom is a motorized uni-slide with an attached horizontal bar. The capacitance probes electronics are mounted on the horizontal bar of the uni-slide. The uni-slide allows precise placements of the probes vertical position, probe emergence, used during static calibration of the probes. Figure 4 shows the longitudinal wave cut hardware in place in the basin. Two probes were used for this experiment. The placements of the probes are referenced to centerline of the model, with probe #1 being the closest inboard and probe #2 the farthest outboard. The probes placements, are documented in Table 3.

Probe Number	Transverse Distance from Model Centerline (y)	y/B
1	1.82 ft (0.56 m)	0.73
2	6.08 ft (15.44 m)	2.44

Table 3 – Longitudinal Wave Cut Probe Locations

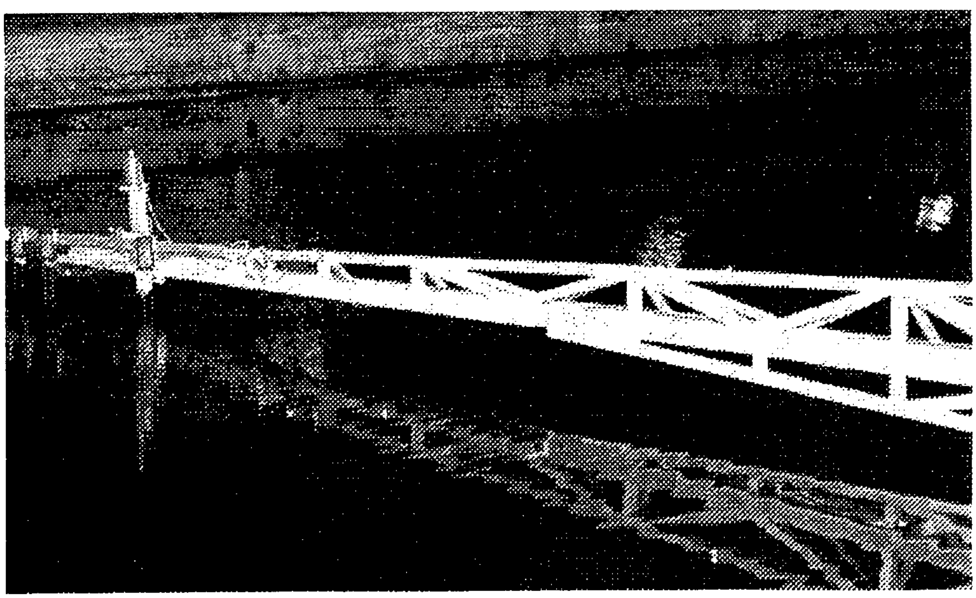

Figure 4 – Longitudinal Wave Cut Set Up

A photo sensor is set to trigger data collection when the forward perpendicular of the model is a predefined distance from the capacitance probes. A 133 MHz. Pentium class personal computer, using an ADC488 16 bit analog to digital (A/D) converter, collects and stores the data.

Calibration

Insitu calibrations are performed after the completion of the test setup. In order to calibrate the probes the motorized uni-slide is traversed in 1-inch (2.54 cm) increments for a total of +/- 3 inches (7.62 cm.) Data are collected at each increment step for each of the probes. A straight line fit is performed and a slope is calculated and stored for each probe. The insitu calibration permits calibration of the probes, the signal conditioning amplifiers, and the A/D converter as a system.

Operating Procedures

Probe zeroes are collected in calm water before each run. The model is then run through the test section, past the probes, at a constant speed. As the model approaches the test section, a strip of reflective tape positioned on the carriage triggers a photosensor placed at the side of the basin which starts data collection. The position of the photosensor and the duration of data collection was adjusted to insure that the maximum amount of data is collected before tank wall reflections occur. Data were filtered at 10 Hz with a 3 pole Bessel filter and collected at a sampling rate of 100 Hz for 20 to 30 seconds depending on model speed and photosensor position.

Data analysis is performed on the PC after each run. First, calibrations are applied to the A/D voltages, and then the probe zeroes are subtracted. The data from each probe is then plotted to ensure that the measurements are of good quality. Further analysis on the longitudinal wave cut data is often performed in order to compute free wave spectra and wave pattern resistance.

STERN TOPOGRAPHY

Theory of operation

The whisker probe is a vertically oriented, mechanized probe, that continuously searches for the free surface. The sensing element of the probe is a .015 inch (0.038cm) diameter, 2 inch (5.08 cm) long stainless steel wire. The wire is mounted into a copper tube which makes up the body of the probe. A geared rack, attached to the probe body, allows the probe to be driven up and down in the vertical plane by a servomotor. Opening and closing a circuit between the probe and the water is sensed by an electronic circuit which drives the servomotor. When the probe is not in contact with the water surface there is an open circuit and the servomotor drives the probe down towards the surface of the water. Once contact is made between the probe and the surface of the water, a closed circuit is sensed and the probe is driven up out of the water. This process is continuously repeated, causing the probe to oscillate at the free surface at approximately 20 Hz. The probe is also geared to a potentiometer to track its position along the z-axis(wave height). Probe position is only recorded by a sample and hold circuit during the instant the probe makes initial contact with the water surface. This manner of sampling probe position alleviates position error, from meniscus effects, due to surface tension.

Experimental Setup

To create a topography of the free surface at the stern of the model, four probes are mounted together on a bracket attached to a uni-slide. The probes are oriented in the longitudinal direction, parallel to the centerline of the model, with 2-inch (5.08-cm) spacing between probes. The probes operating behind Model 5415 can be seen in Figure 5. The array of probes are attached to an X-Y traverse that is mounted to the carriage at the stern of the model. Two string pots are attached to the traverse and used to track the longitudinal(X) and transverse (Y) positions of the probes. A 33 MHz 486 class personal computer, using a ADC488 16 bit A/D converter, collects and stores the data. The collection computer is networked with a 350 MHz Pentium II class laptop computer which is used for data analysis and plotting. Data were filtered at 10 Hz with a 3 pole Bessel filter and collected at a sampling rate of 100 Hz.

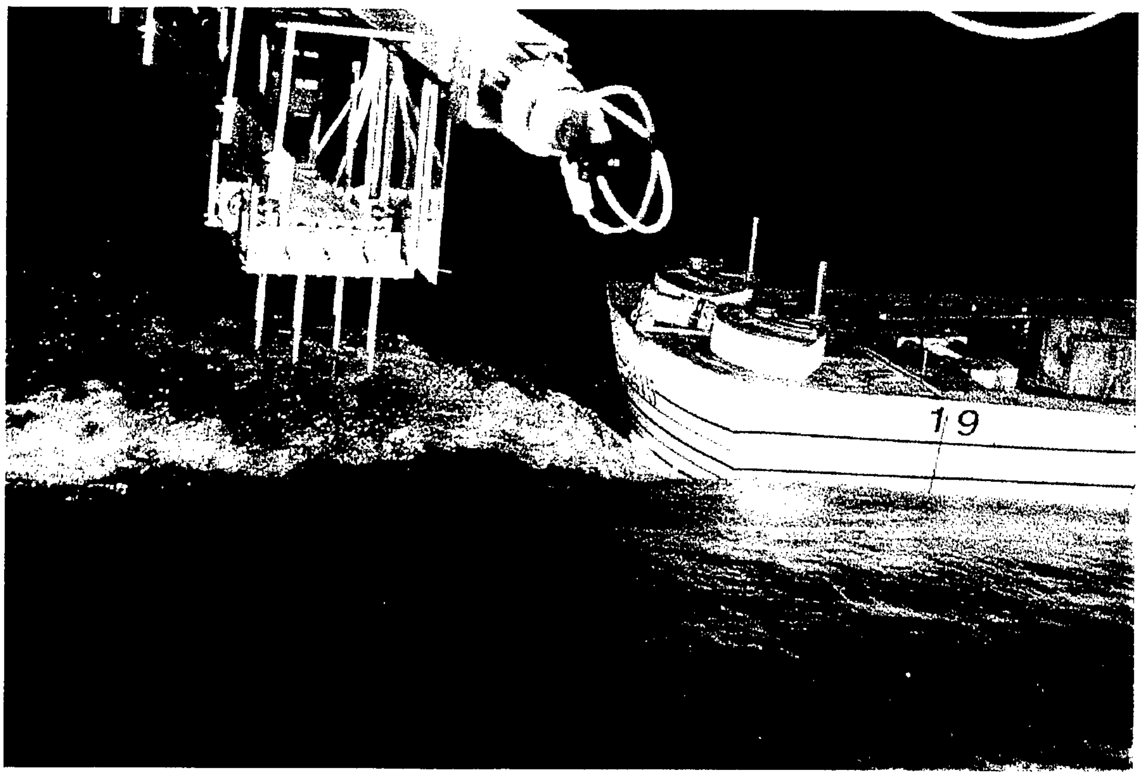

Figure 5 – Whisker probes operating behind Model 5415

Calibration

Static calibrations are performed on the whisker probes in the lab, prior to the experiment. Probes are mounted together on a bracket, and attached to a uni-slide. The probes are positioned over a container of water, and allowed to track the calm free surface as the uni-slide is traversed in 1 inch (2.54 cm) increments for a total of +/- 3 inches (7.62 cm). Data are collected at each increment step for each of the probes. A straight line fit is performed and a slope is calculated and stored for each probe.

Operating Procedures

The forward most probe is aligned longitudinally (X) and transversely (Y) with the aft perpendicular and centerline of the model respectively. The longitudinal and transverse string pots are zeroed at this location, and all future measurements are referenced to this position. In order to collect the data needed to generate a complete topography of the stern area, the area is divided into a number of transverse cuts. The possible number of transverse cuts per run is dependant on model speed. Once the number of traverse cuts per run is determined, a command file is generated which controls the positioning of the probes during the run. Using four probes spaced 2 inches (5.08 cm) apart along the x-axis, one transverse cut collects an area of 6 inches x 52 inches (15.24cm x 132cm). Starting as close to the stern of the model as possible ½ inch (1.27cm), successive transverse cuts are made with an advancement of 8 inches (20.32 cm) along the x-axis between cuts. Prior to each run a zero collection is performed. A zero run consists of performing an identical collection run of transverse cuts, but with the model stationary. This procedure eliminates bias errors due to misalignment or sagging of the traverse's X-Y plane and the surface of the water, which should be parallel to one another. After the zero run is performed, the model is brought up to a constant speed and a collection of transverse cuts are started. This process is repeated at successive transverse locations until the desired area behind the model has been completely mapped. For this experiment the completed mapped area measured 52 inches x 94 inches (1.32m x 2.38m).

Analysis of the stern topography data is done by applying the calibration factor to the A/D voltages from the at-speed data and the zero-speed data, and then subtracting out the zero-speed data to produce a set of zero-compensated data. Next, filter coefficients are calculated for a Butterworth filter with an optional number of poles, chosen by the user (in this case, 3 poles were specified.) The zero compensated probe data is then filtered in both directions to eliminate data phase shifts. The next step before plotting, is to extract data from the data set. A grid pattern is established with an x-value at every longitudinal probe position and a y-value which starts at the beginning of each transverse probe position and extends to the ending probe position, in increments of 0.5 cm. Probe data closest to the desired grid locations are extracted from the data set and saved. These data are then placed into a format for plotting the stern topography contour maps, using TECPLOT software. It is important to note that these contour maps represent the average of a time-varying data set with an RMS variation about the mean contour level.

PRESENTATION AND DISCUSSION OF RESULTS

The coordinate system for the measurements is difined with the x-axis being parallel to the model centerline, the y-axis athwartships and the z-axis perpendicular to the calm water surface. All data and axes have been non-dimensionalized using the model length. The forward perpendicular is denoted at x/L=0, and the aft pependicular as x/L=1.0.

Longitudinal Wave Cut Measurements

Longitudinal wave cuts for Model 5415 with and without propellers operating, at Froude numbers of 0.28 and 0.41, are shown in Figures 6 and 7. A longitudinal wave cut can be characterized by four waves or wave systems. The first wave is the "bow wave," generated by the bow and shoulder. The bow wave is followed by the waves generated along the mid-body, followed by a "stern wave," generated by the stern. Lastly a set of transverse waves decaying behind the model are observed. At a Froude number of 0.28, at the inner probe location of y/B of 0.73, the effect of propulsion is dominant in the transverse wave system aft of the model. With the propellers operating at 436 RPM, there is a 10 percent increase in the transverse wave heights over the unpropelled case. The effect of the operating propeller is particularly noticeable in the amplitude of the stern wave, which is augmented by 20 percent. At the outer probe location (y/B is 2.44) the effect of propulsion on the stern wave is less; only accounting for an increase of 10 percent. There is also a noticeable phase shift in the transverse wave system between the unpropelled and propelled condition. The transverse wave system of the propelled model is shifted aft by 12 percent of the transverse wave length (2 V^2/g). This phase shift is more evident at large values of x/L.

At a Froude number of 0.41, where the propellers operate at 722 RPM, propulsion has a minimal effect on the wave system, accounting for only a 6 percent increase in the stern wave amplitude and 2 percent increase in the amplitude of the transverse wave system at the inner probe location. At the outer probe location, propulsion accounts for a 9 percent increase in the stern wave amplitude and a negligible increase in the amplitudes of the transverse wave system. At this speed, the large stern wake is dominated by the flow around the transom stern, so the effect of the operating propellers is less evident than at a Froude number of 0.28.

The effect of propulsion on the longitudinal wave cuts generated by a model representing another combatant hull form has been shown to be larger than seen here for Model 5415. This data set is presented in Reference 3.

Stern Topography

A comparison of the propelled and unpropelled near-field wave systems at a Froude number of 0.28, measured with the whisker probe, is shown in Figure 8. The difference between the two conditions has been quantified in Figure 9. Propulsion increases the wave amplitudes along the stern wave crest line on the order of 35 percent. In the region behind the stern, between an x/L of 1.05 and 1.15, propulsion effects account for local increases in wave heights of 25 to 35 percent. At this Froude number the flow is still attached to the transom.

At a Froude number of 0.41, the transom is completely clear (dry) and the flow converges in a highly turbulent region covering an area of 0.15 ship lengths, longitudinally by 0.05 ship lengths, transversely. Figure 10 shows the differences due to propulsion in the wave field behind the transom at a Froude number of 0.41. Figure 11 serves to quantify those differences. The differences due to propulsion at this higher Froude number are more scattered over the complete stern area than was the case for the Froude number of 0.28. The effect of propulsion accounts for differences on the order of 20 percent in two regions; along the stern wave crest and, aft of the transom. The area aft of the transom, located at an x/L of 1.2 is farther downstream than the affected area at a Froude number of 0.28. At this higher Froude number, the propellers have a smaller effect on the stern wave system than they do at a Froude number of 0.28.

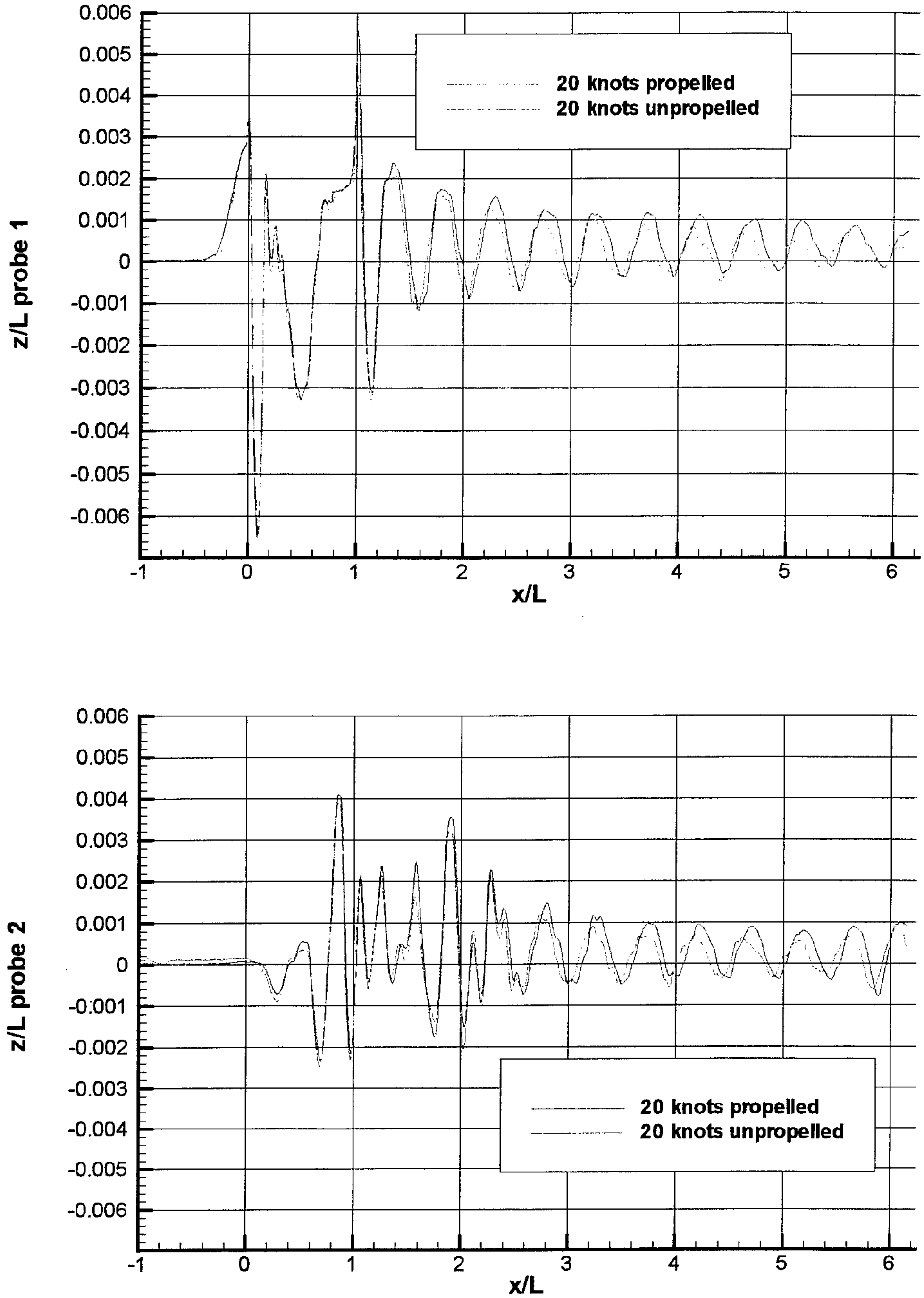

Figure 6 – The Effect of Propulsion on the Far Field Wave System as Measured with Stationary Capacitance Probes, at a Froude number of 0.28

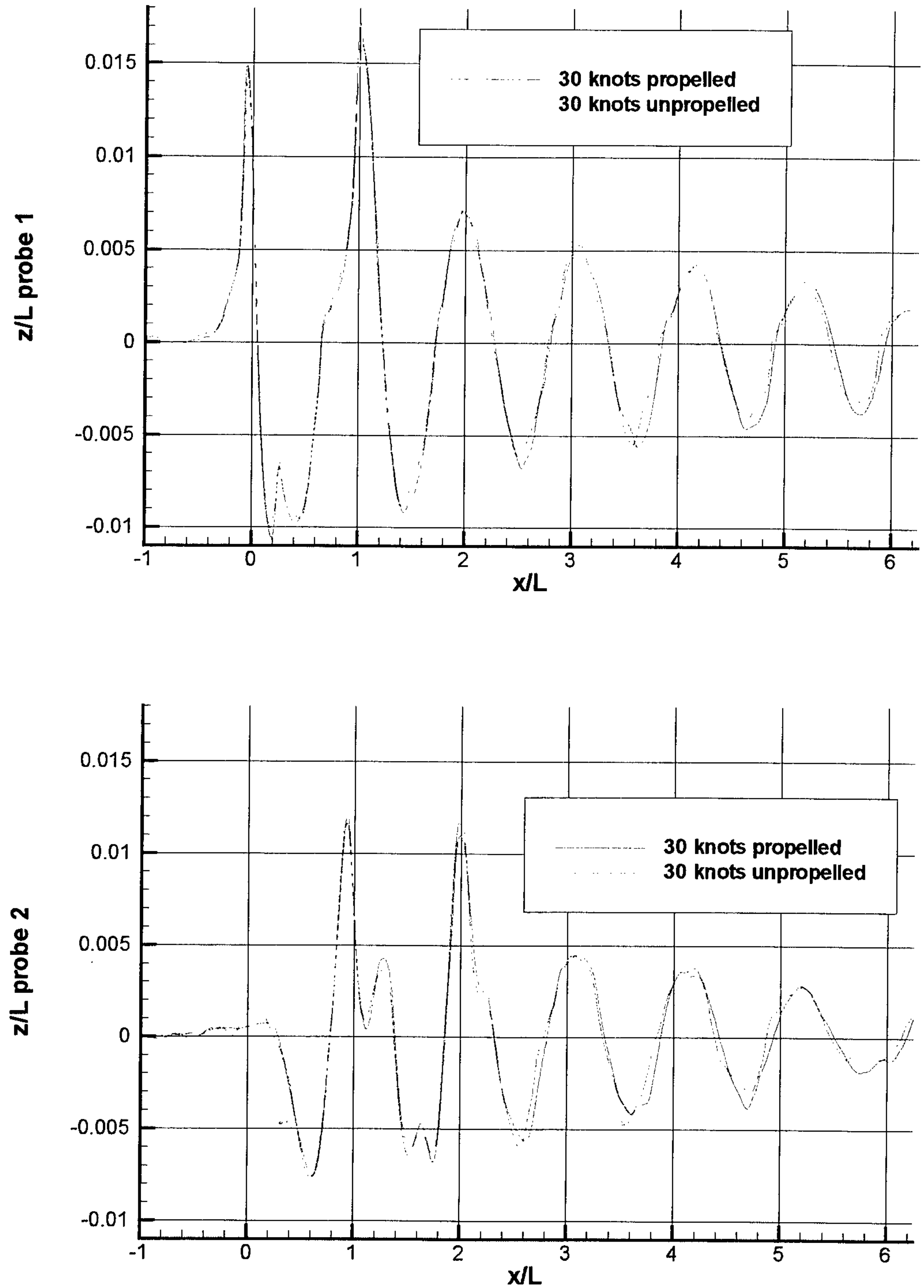

Figure 7 – The Effect of Propulsion on the Far Field Wave System as Measured with Stationary Capacitance Probes, at a Froude number of 0.41

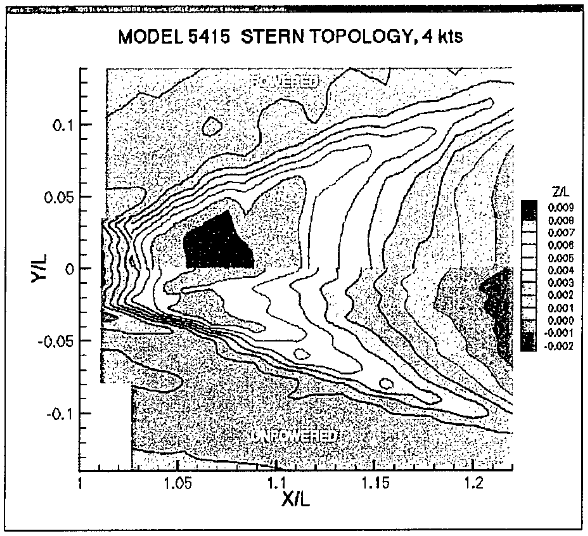

Figure 8 – The Effect of Propulsion on the Near Field Wave System of Model 5415 as Measured with Whisker Probes, at a Froude number of 0.28

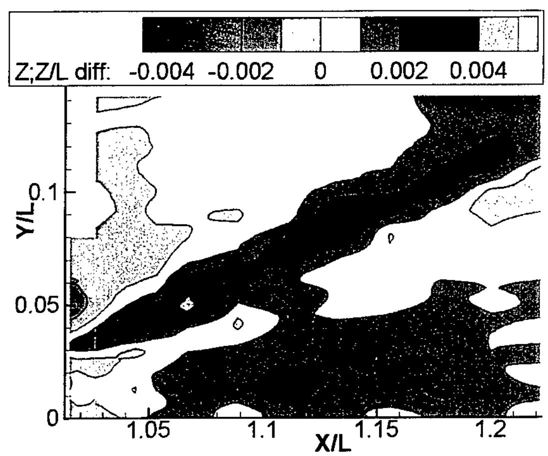

Figure 9 – Stern Topography Differences (Propelled-Unpropelled) in the Near Field Wave System of Model 5415 at a Froude number of 0.28

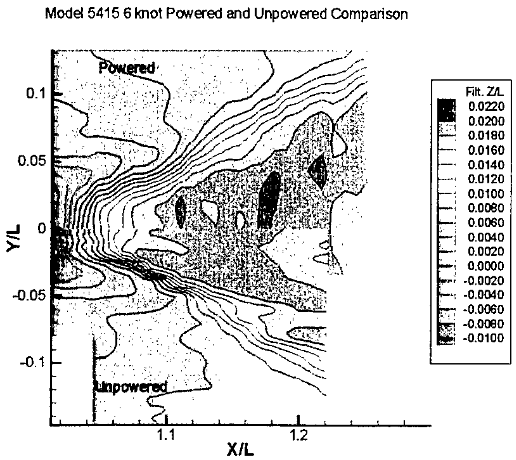

Figure 10 – The Effect of Propulsion on the Near Field Wave System of Model 5415 as Measured with Whisker Probes, at a Froude number of 0.41

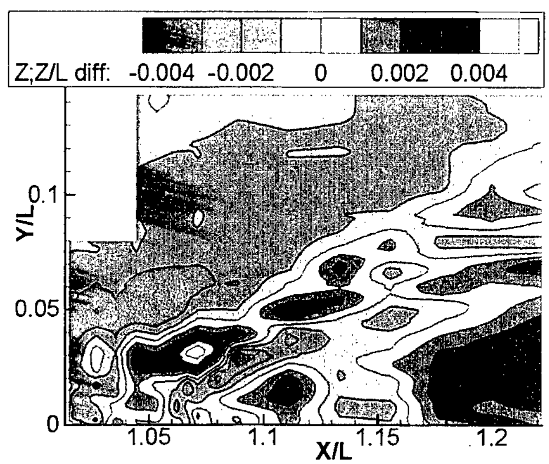

Figure 11 – Stern Topography Differences (Propelled-Unpropelled) in the Near Field Wave System of Model 5415 at a Froude number of 0.41

MEASUREMENT UNCERTAINTY

Measurement uncertainty has been determined for both the longitudinal wave cut and whisker probe data, at each of the two speeds where data were obtained. The analysis is in accordance with standard uncertainty analysis practices of the "Guide to the Expression of Uncertainty in Measurement" as documented in 1993 by the International Organization for Standardization (ISO), and explained further in Reference 4 and the Reference 5. Detailed explanations and examples of the uncertainty analysis are given Coleman and Steele (1998).

For each speed and condition at which wave cuts were conducted, a mean wave was calculated from the repeat passes that were collected. The mean wave from these repeat passes was calculated by averaging Z/L (the wave heights), at each X/L, (the longitudinal distance from the aft perpendicular). Seven repeat passes were collected at a Froude number of 0.28 for the propelled and unpropelled condition, and eight repeat passes were collected at a Froude number of 0.41. For the whisker probe data, transverse cuts were used to calculate the mean waves in the transverse direction (Y/L). Six repeat runs were obtained at a Froude number of 0.28 and nine at a Froude number of 0.41.

The precision limits are based on the standard deviations of the wave. The standard deviation at each X/L or Y/L location is calculated when the mean wave is averaged from the repeat passes. The standard deviations across the whole wave are multiplied by the proper student-t value scalar from the 95% certainty curve to produce the precision limits. These precision limits, vary with the position in the wave, usually greater at the crests and troughs of the wave than at the zero-crossings.

The bias limit is determined by calibrations done insitu and are a scalar applied across the entire mean wave. The uncertainty is computed by the root-sum-square of the bias and precision limits (also commonly referred to as the systematic and random errors).

The combined uncertainty for the propelled and unpropelled conditions are presented in Table 4.

	Bias Error (% of total uncertainty)	Precision (Random) Error (% of total uncertainty)	Total Uncertainty (% of largest value)
Fn=0.28 *Longitudinal Wavecuts*	86	14.0	2.73
Stern Topography	64.8	35.2	4.60
Fn=0.41 *Longitudinal Wavecuts*	66.4	33.6	3.54
Stern Topography	32.4	67.6	9.20

Table 4 – Summary of Measurement Uncertainty for Longitudinal Wavecuts and Stern Topography at Two Speeds

CONCLUSIONS

These data provide a comprehensive documentation of the effect of propulsion on the wave system around a naval combatant hull form. The use of both near- and far-field measurement systems results in a thorough mapping of the wave field around this hull form. The data presented here shows that there is a greater effect of propulsion on the wave system near the model at Froude number of 0.28 than at a Froude number of 0.41. It is likely that this is due to the different nature of the hydrodynamic flow at each of these Froude numbers. At a Froude number of 0.28, the flow is still attached to the transom and the effect of the operating propellers is to change the character of the local wave system. This change is manifested as an increase in the maximum wave heights along the stern wave crest line and an increase in the wave heights behind the model. At a Froude number of 0.41, where the transom is dry, the flow field is dominated by the flow at the edges of the transom converging astern, and the effects of the operating propellers are smaller than were observed at a Froude number of 0.28.

It is hoped that these data will continue to provide an insight into the effect of propulsion on the hydrodynamic flow around transom stern models, and will be used to evaluate the way in which computational fluid dynamics prediction codes model propulsors in the computations.

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